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Indications of partial chiral symmetry restoration from pionic atoms

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Abstract

Extensive data on strong interaction effects in pionic atoms are analyzed with a density-dependent isovector scattering amplitude suggested recently by Weise to result from a density dependence of the pion decay constant. Most of the so-called 'missing s-wave repulsion' is removed when adopting this approach, thus indicating a partial chiral symmetry restoration in dense matter. The resulting potentials describe quite well also elastic scattering of 20 MeV pions on Ca. Further tests with elastic scattering are desirable.

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The interaction of low energy pions with nuclei has been known for years to be described well by a theoretically-motivated phenomenological optical potential [1], particularly at zero energy where strong interaction effects in pionic atoms have been studied extensively both experimentally and theoretically [2]. The traditional method of spectroscopy of pionic X-rays has been supplemented very recently by the observation of 'deeply bound' pionic atom states through the $(d,{}^3\mathrm{He})$ reaction [3,4], thus adding a new dimension to the ability to study pion interactions at threshold in the nuclear medium. Whereas the p-wave part of the pion–nucleus optical potential, which is effective only near the nuclear surface, is described rather well by the free pion–nucleon amplitudes (plus a phenomenological two-nucleon absorption term), this is not the case for the s-wave part of the potential. This part of the potential, which is effective throughout the nuclear volume, is a natural source of information on possible modifications by the nuclear medium of the pion–nucleon interaction. This is the topic of the present Letter which deals with the strong s-wave repulsion of pions in nuclear matter and its possible origins in a density dependence of the pion decay constant which reflects the change of QCD vacuum structure in dense matter.

The interaction between low energy pions and nuclei is traditionally described [2] by an optical potential as follows:

$$2\mu V_{\mathrm{opt}}(r) = q(r) + \vec{\nabla}\cdot\alpha(r)\vec{\nabla}, \tag{1}$$

with the s-wave part given by

$$q(r) = -4\pi\left(1+\frac{\mu}{M}\right)\Big\{\bar{b}_0\big[\rho_n(r)+\rho_p(r)\big] + b_1\big[\rho_n(r)-\rho_p(r)\big]\Big\}$$

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$$-4\pi\left(1+\frac{\mu}{2M}\right)4B_0\rho_n(r)\rho_p(r), \tag{2}$$

where ρ_n and ρ_p are the neutron and proton density distributions normalized to the number of neutrons N and number of protons Z, respectively, μ is the pion–nucleus reduced mass and M is the mass of the nucleon. The parameter $\bar{b}_0$ is given in terms of the pion–nucleon (minus) isoscalar and isovector scattering lengths b_0 and b_1, respectively,

$$\bar{b}_0 = b_0 - \frac{3}{2\pi}\left(b_0^2 + 2b_1^2\right)k_{\mathrm{F}}, \tag{3}$$

where k_{F} is the local Fermi momentum. This second order term is included because of the extremely small value of b_0 [5] and it will be shown to play a decisive role in what follows. The term with the complex parameter B_0 represents absorption on a neutron–proton pair. The term with $\alpha(r)$ is referred to as the p-wave potential, see Eqs. (20)–(22) of [2].

Values of the various parameters of the potential are obtained from fits to experimentally determined strong interaction level shifts and widths and 'upper' level yields. Modern data sets containing at least 50 data points along the periodic table lead to rather well defined values for the various parameters and to good agreement between calculation and experiment, with typically χ^2 per point of about 2. Addressing the real part of the s-wave potential, it has been found [2] that both b_0 and $\mathrm{Re}\, B_0$ are well determined by the data, contrary to earlier conclusions [6] which were based on considerably more restricted data. A somewhat confusing situation arises when values of $\mathrm{Re}\, B_0$ are found to be large and repulsive, i.e., 3 to 5 times larger than the values of $\mathrm{Im}\, B_0$, whereas expectations are that $\mathrm{Re}\, B_0$ is attractive and of about the same magnitude as the imaginary part. This unexpected phenomenological repulsion has been referred to as a 'missing repulsion' [2,7].

In the present work fits have been made to 60 experimental values of level shifts, widths and upper level yields for targets from ^{16}O to U, including the very recently determined binding energies and widths for the deeply bound $1s$ and $2p$ states in ^{205}Pb [8,9]. As the parameters of the linear term of the p-wave part of the potential were always found to be very close to the free pion–nucleon values when the Lorentz–Lorenz parameter ξ was close to 1, we have kept subsequently these parameters fixed at the free pion–

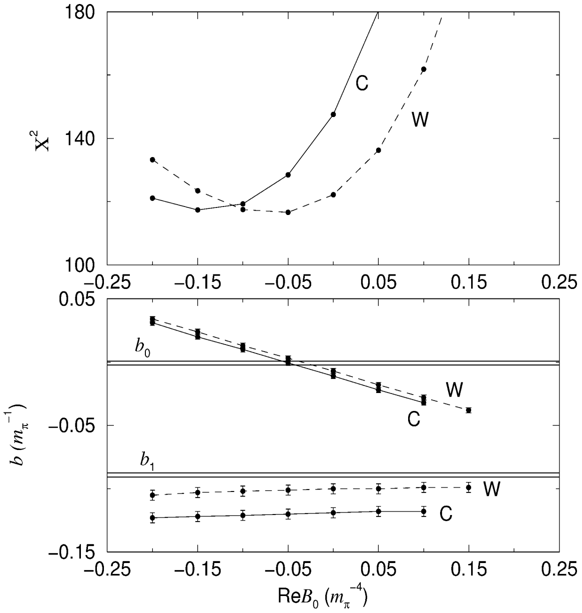

Fig. 1. Fits to pionic atom data as function of $\mathrm{Re}\, B_0$. Upper part: values of χ^2, lower part: values of b_0 and b_1. Also shown as horizontal bands are values of b_0 and b_1 for the free pion–nucleon interaction. C stand for the conventional potential, W stand for the Weise prescription (Eq. (5)).

nucleon values together with $\xi = 1$ and varied only the parameters of the s-wave part of the potential and the phenomenological quadratic (absorptive) term in the p-wave part. The latter, traditionally denoted by C_0, was found to be independent of variations in the s-wave part of the potential and its real part was essentially zero. In order to focus on the various components of the real part of the s-wave potential, we show in Fig. 1 results of such fits, as a function of the parameter $\mathrm{Re}\, B_0$. The upper part shows values of χ^2 for the 60 data points and the lower part shows the corresponding values of the other parameters of the real part of the s-wave potential, namely, b_0 and b_1. The values of $\mathrm{Im}\, B_0$ were found to be remarkably constant at $0.056 m_\pi^{-4}$. Also shown as horizontal bands in the lower part are the free pion–nucleon values of b_0 and b_1 which have been determined very recently to high precision [5].

Three features are easy to observe from the solid curves labelled 'C': (i) the values of all three parameters are well determined, (ii) the parameter $\mathrm{Re}\, B_0$ is repulsive and large ($\mathrm{Re}\, B_0 \approx -3\, \mathrm{Im}\, B_0$) and (iii) b_0

Table 1
Parameter values from fits to 60 pionic atom data points. Other p-wave parameters were held fixed at $c_0 = 0.22m_\pi^{-3}$, $c_1 = 0.18m_\pi^{-3}$ and $\xi = 1$. The free pion–nucleon values [5] are $b_0 = -0.0001^{+0.0009}_{-0.0021} m_\pi^{-1}$ and $b_1 = -0.0885^{+0.0010}_{-0.0021} m_\pi^{-1}$

Potential	χ^2	b_0 (m_π^{-1})	b_1 (m_π^{-1})	Re B_0 (m_π^{-4})	Im B_0 (m_π^{-4})	Im C_0 (m_π^{-6})
C	117.3	0.018 ± 0.010	-0.122 ± 0.004	-0.14 ± 0.04	0.056 ± 0.002	0.056 ± 0.004
W	116.3	0.007 ± 0.009	-0.102 ± 0.004	-0.06 ± 0.04	0.056 ± 0.002	0.056 ± 0.004
W65	117.7	0.001 ± 0.009	-0.095 ± 0.004	-0.03 ± 0.04	0.055 ± 0.002	0.055 ± 0.004
CB	118.2	0.005 ± 0.010	-0.110 ± 0.004	0.00 ± 0.04	0.056 ± 0.002	0.056 ± 0.004
WB	118.3	-0.004 ± 0.010	-0.092 ± 0.004	0.06 ± 0.04	0.055 ± 0.002	0.056 ± 0.004

and b_1 are well determined and are significantly different from the corresponding free pion–nucleon values. Note that the parameter b_1 is found to be more than 35% larger in absolute value than its free pion–nucleon value and that it contributes significantly to the repulsion, also in $N = Z$ nuclei, through the b_1^2 term in Eq. (3). In fact, for ^{40}Ca it contributes as much as 35% of the real potential. Thus the 'missing repulsion' appears as a very repulsive dispersion term Re B_0 *and* an enhanced b_1 parameter. This information is lost when one adopts the 'effective density' approach of lumping together b_0 and Re B_0 [6,10]. As the free pion–nucleon b_0 is extremely small and the empirical values of b_0 are much smaller than values of b_1, we discuss only the b_1 parameter, where the extra repulsion observed may be associated with medium modification of the pion–nucleon interaction.

The in-medium s-wave interactions of pions have been discussed very recently by Weise [11] in terms of partial restoration of chiral symmetry in dense matter where the isospin-odd in-medium pion–nucleon amplitude is inversely proportional to the square of the pion decay constant f_π. The square of the latter is given, in leading order, as a linear function of the nuclear density,

$$f_\pi^{*2} = f_\pi^2 - \frac{\sigma_N}{m_\pi^2}\rho \tag{4}$$

with σ_N the pion–nucleon sigma term. This leads to a density-dependent isovector amplitude such that b_1 becomes

$$b_1(\rho) = \frac{b_1(0)}{1 - 2.3\rho} \tag{5}$$

for $\sigma_N = 50$ MeV and with ρ in units of fm^{-3}. Note that expanding this expression in powers of the density leads naturally to a repulsive ρ^2 term in the pion–nucleus potential. We have introduced this expression for b_1 into the potential, using for ρ the local nuclear density $\rho(r)$ and repeated the fits to the experimental results. The idea here is to check the consequences of prescription (4) by applying it to modern and extensive pionic atom data. Possible modifications of B_0 are not considered because we treat this parameter all along as purely phenomenological. The dashed curves labelled 'W' in Fig. 1 show the results obtained with this prescription. From the minimum of χ^2 it is clear that now Re B_0 is considerably less repulsive (Re $B_0 \approx -$ Im B_0) and that b_0 agrees with the free pion–nucleon value. The value of b_1 is now much closer to the free pion–nucleon value, although still a little more repulsive. It is seen, therefore, that the introduction of the theoretically motivated medium dependence into the repulsive terms containing b_1 removes a major fraction of the excessive phenomenological repulsion, as evidenced by the significantly reduced magnitude of both b_1 and Re B_0. The best fit parameters for the above potentials are summarized in the first two rows of Table 1. The third row ('W65') is for the same prescription but with a larger value for the pion–nucleon sigma term of $\sigma_N = 65$ MeV (not shown in the figure). It is seen from the table that for this value of σ_N the empirical b_0 and b_1 parameters are consistent with the free pion–nucleon values. Higher order terms have also been considered very recently [12] and found to be small.

Among several previous attempts to account for the missing s-wave repulsion we mention a relativistic impulse approximation (RIA) approach [13] which showed, following Birbrair and others [14–16], that a specific version of the RIA is able to provide

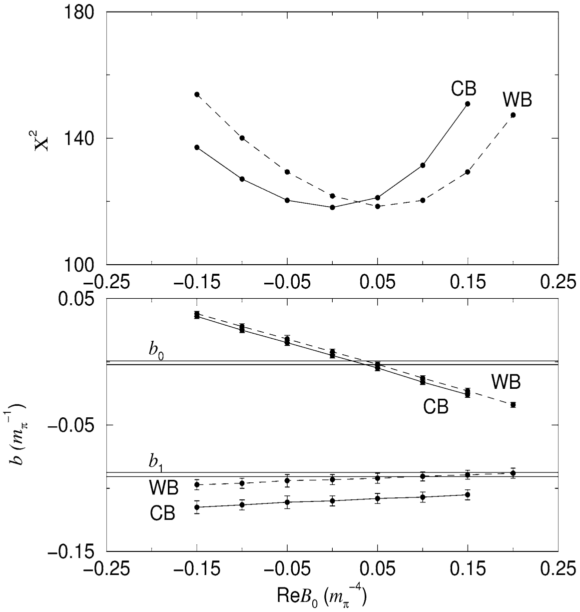

Fig. 2. Same as Fig. 1 but with the RIA term included. CB stand for the conventional potential, WB stand for the Weise prescription.

a significant part of the missing repulsion through the modification of the *nucleon* mass in the nuclear medium. We have, therefore, looked again into this possibility, noting, however, that in Ref. [13] it was shown that there was *no unique* way of introducing RIA effects into the pion–nucleus interaction [17]. This specific version of the RIA was included using the following parameterization [16]

$$\frac{M(\rho)}{M(0)} = \frac{1}{1+a\rho} \tag{6}$$

with $a = 2.7\ \mathrm{fm}^3$, amounting to $M(\rho)/M(0) = 0.7$ for the nucleon mass ratio at normal nuclear density. The results are shown in Fig. 2 where it is seen that when the RIA correction is applied to the conventional potential ('CB', solid curves) no repulsion is required through the B_0 term, but the values of b_0 and b_1 are still not in agreement with the free pion–nucleon values. Also seen from the figure is that when the RIA term is included together with the theoretically motivated density dependence of b_1 Eq. (5) ('WB' dashed curves), an *attractive* Re B_0 is found whose magnitude is close to the magnitude of the absorptive part and, then, both b_0 and b_1 agree with the corresponding free pion–nucleon values. The best fit values of the potential parameters for these two versions of the potential (with $\sigma_N = 50$ MeV) are also summarized in Table 1.

The value of the real potential at the center of the ^{208}Pb nucleus has received some attention recently [18,19]. All five potentials yield values between 34 and 39 MeV for this quantity. Obviously these values are extrapolated from the better determined values of the potential near the nuclear surface. Taking, e.g., the real potential at the 50% density point, then all five potentials yield values between 12.4 and 13.7 MeV for this quantity.

It is interesting to study the above mentioned features at energies just above threshold through the elastic scattering of low energy pions by nuclei, thus testing further the validity of the chirally motivated approach. Indeed it has been shown [6,20,21] that pion–nucleus potentials develop smoothly from the bound states regime to the elastic scattering regime. Here we examine only the elastic scattering of 19.5 MeV pions by Ca with the help of the experimental results of Wright et al. [22] which seem to be the only fairly extensive data for π^+ and π^- on the same nucleus and from the same experiment at such low energies. Using the parameters of Table 1 we have calculated the differential cross sections for elastic scattering of pions by Ca at 19.5 MeV and found reasonable agreement with the data. The agreement with the data is a little better for the two potentials that include the RIA corrections (last two rows of the table). Fig. 3 shows comparisons between experiment and calculations for these two potentials. Improving the agreement by adjusting the complex parameter B_0, we find that the values of Im B_0 hardly change at all but Re B_0 has to be made a little more repulsive, typically by $0.02m_\pi^{-4}$. Alternatively, if b_0 is adjusted, the extra repulsion is compatible with the energy dependence of this parameter. It is, therefore, concluded that the limited experimental results for elastic scattering of very low energy pions by nuclei support the picture that emerges from the extensive studies of pionic atoms regarding the nature of the missing s-wave repulsion. However, the data on elastic scattering are for one nucleus only, whereas we have included 23 nuclei in the study of pionic atoms. Therefore, precision data for the elastic scattering of very low energy $\pi^\pm$ on some additional nuclei are desirable.

In conclusion, we have shown that most of the 'missing s-wave repulsion' in the interaction of pions

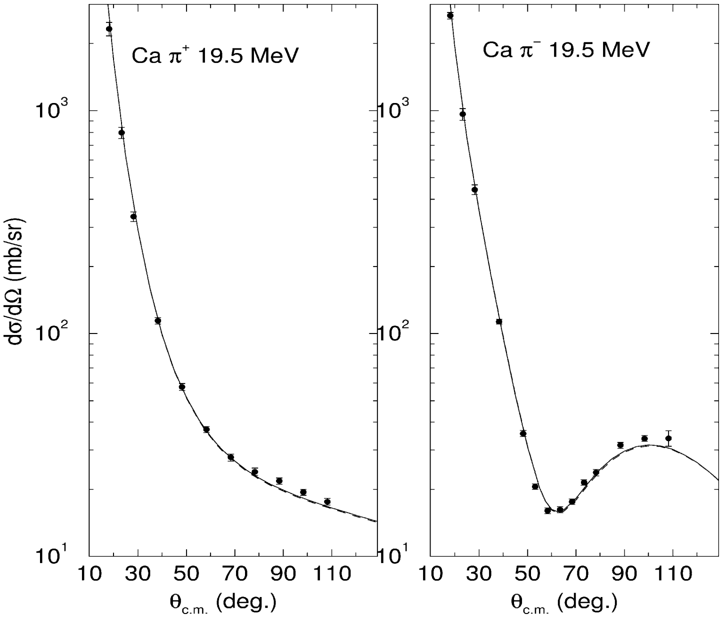

Fig. 3. Elastic scattering of 19.5 MeV pions by Ca. Experimental results from [22]. Solid lines: potential CB of Table 1, dashed lines: potential WB of the table.

at threshold with nuclei can be removed by adopting a density-dependent isovector amplitude as suggested by Weise [11] to result from a density dependence of the pion decay constant. The underlying picture is that of partial restoration of chiral symmetry in dense matter. This applies, however, only to the b_1 parameter of the optical potential because the quadratic terms were kept in the present work as purely phenomenological quantities. When an additional, although not unique, RIA term is included, the best fit pionic atom potential is in full agreement with the chirally motivated model based on the *free* pion–nucleon amplitudes.

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